Selecting a Laboratory Loose Mix Aging Protocol for the NCAT Top-Down Cracking Experiment

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ABSTRACT

The objective of this study was to select a laboratory loose mix aging protocol for the NCAT top-down cracking (TDC) experiment. Literature review was first conducted to determine a critical field aging condition for evaluating TDC. In this study, field aging of asphalt mixtures was characterized using the cumulative degree-days (CDD), which was defined as the accumulation of daily high temperature throughout mixtures' service life. Performance data from a number of existing pavements showed that TDC typically initiated after approximately 70,000 CDD. A laboratory experiment was then conducted to select an aging protocol that was representative of this critical CDD. Materials used in the experiment were from five projects in Michigan, Washington, and Alabama. Four loose mix aging protocols were evaluated in terms of their effects on the rheological and oxidation properties of asphalt binders. Results from the dynamic shear rheometer (DSR), bending beam rheometer (BBR), and Fourier Transform Infrared Spectroscopy (FT-IR) tests showed that the 24-hour, 135°C protocol yielded the most significant level of asphalt aging, followed by the 12-hour, 135°C protocol, 5-day, 95°C protocol, and 6-hour, 135°C protocol, respectively. No significant difference in the oxidation-hardening relationship of asphalt binders was observed for mixes aged at 95°C versus 135°C. Among the four aging protocols, the 5-day, 95°C protocol was most representative of 70,000 CDD of field aging. Finally, DSR and FT-IR results indicated that loose mix aging of 8 hours at 135°C and 5 days at 95°C were likely to achieve an equivalent aging level; thus, the 8-hour, 135°C protocol was recommended as an alternative protocol to simulate 70,000 CDD of field aging.

Keywords: Top-down cracking, laboratory loose mix aging, field aging, rheology, oxidation

1. INTRODCUTION

Top-down cracking (TDC) has been widely reported as a common type of distress in asphalt pavements. Different from the traditional bottom-up cracking, TDC initiates at the surface of the asphalt pavement and progresses downward to the bottom of the asphalt layers. TDC is typically longitudinal with surface crack widths around 3 to 4 mm and decreasing with pavement depth (*1-2*). Over the past few decades, several factors have been identified that contribute to the development of TDC. These factors include high bending-induced surface tension and shear-induced near-surface tension due to tire-pavement interactions, age hardening of asphalt binder, and lower stiffness of upper HMA layers (*3*). Despite a number of cracking tests are currently available for evaluating the cracking potential of asphalt mixtures, there is not a consensus among the asphalt pavement industry regarding the most appropriate method to address TDC.

In 2015, the National Center for Asphalt Technology (NCAT) partnered with the Minnesota Department of Transportation's Road Research facility (MnROAD) for a national-level pavement cracking study. The overall objective of the study is to validate laboratory cracking tests by establishing correlations between test results and measured cracking in real pavements using real loading conditions. Test sections were built on the NCAT Test Track and MnROAD to evaluate TDC and thermal cracking tests, respectively. Seven mixtures with a wide range of cracking potentials were included in the experiment that focused on TDC evaluation (hereinafter referred to as the NCAT TDC experiment). Each mixture was constructed as the 1.5-inch surface layer on the NCAT Test Track on top of highly polymer modified base and binder layers. The base and binder layers were intentionally designed to be highly elastic to mitigate the occurrence of bottom-up cracking (*4*-*5*). The laboratory experiment consisted of five cracking tests: energy ratio, Texas overlay, NCAT-modified overlay, semi-circular bend (SCB), and Illinois flexibility index (I-FIT) tests. Considering the importance of age hardening of asphalt mixtures in the development of TDC, both laboratory-mixed laboratory-compacted (LMLC) and plant-mixed laboratory-compacted (PMLC) specimens would be short-term conditioned and long-term aged prior to testing.

The standard practice for laboratory long-term oven aging (LTOA) per AASHTO R 30 is to condition a compacted specimen for five days at 85°C. This protocol, which was initially developed in a pre-SHRP study by Bell et al. (*6*), is anticipated to simulate field aging of asphalt pavements over seven to ten years of service. However, the National Cooperative Highway Research Program (NCHRP) project 09-52 reported that this protocol was only representative of approximately one or two years of field aging in warmer climate and colder climate, respectively (*7*). The conclusion was obtained based on the resilient modulus (M_R) and Hamburg wheel tracking test (HWTT) results of LMLC specimens and field cores for over 40 different asphalt mixtures. Similar findings were also reported by Islam and Tarefder (*8*) and Howard et al. (*9*) in bending beam fatigue (BBF) and Cantabro tests, respectively.

In addition to conditioning compacted specimens, LTOA can be conducted by aging asphalt loose mix prior to compaction. The latter protocol typically yields a more severe level of aging due to increased exposure of asphalt mix to oxygen and elevated temperature. The loose mix aging process can be further accelerated using a higher temperature without concerns of specimen distortion (i.e., changes in specimen air voids and geometry) (*10*). Over the past few years, several loose mix aging protocols have been used by different researchers. Braham et al. (*11*) conditioned the loose mix at 135°C for 24 hours and evaluated its effect on mixture fracture energy from the disk-shaped compact tension (DCT) test. In another study conducted by Reinke et al. (*12*), loose mix from three MnROAD test sections were conditioned at 135°C for 12 and 24 hours prior to being compacted for mixture testing. The NCHRP project 09-54 evaluated loose mix aging at multiple temperatures ranging from 70°C to 135°C (*13*). It was reported that, for certain asphalt binders, there was a significant change in the relationship between binder rheology and chemistry when the aging temperature increased from 95°C to 135°C. A reduction in mixture fatigue resistance was also observed for mixtures aged at 135°C. Therefore, the authors recommended an optimal loose mix aging temperature of 95°C.

Although the above-mentioned aging protocols seemed promising for use in mix design and performance testing, their correlations with field aging have not been identified. In addition, the traditional expectation of LTOA to simulate seven to ten years of field aging may not be appropriate to evaluate TDC, since most of these cracks were reported to develop within a significantly shorter period (i.e., three to five years) (*1-2, 14*). Therefore, the objectives of this study were set to: (1) identify a critical field aging condition when TDC starts to develop, and (2) select a representative laboratory aging protocol to age asphalt mixtures for the NCAT TDC experiment.

2. IDENTIFICATION OF CRITICAL FIELD AGING FOR TDC

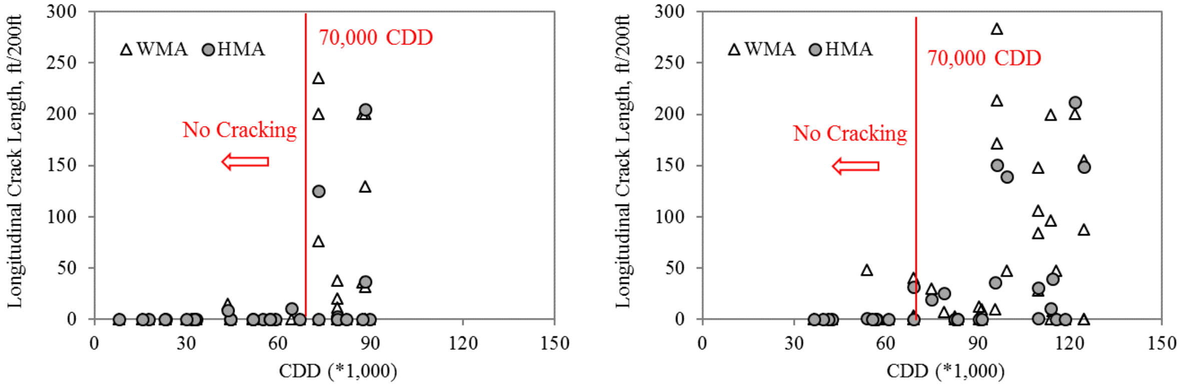
Pavement in-service time at the time of coring was a commonly used parameter to quantify field aging of asphalt mixtures. This parameter, however, failed to differentiate the aging of pavements with different climates and construction dates. Generally, field aging is more severe in warmer climate than in colder climate given the same aging time. In NCHRP project 09-52, the cumulative degree-days (CDD) parameter was proposed to overcome this shortcoming (*7*). As expressed in Equation (1), CDD was defined as the accumulation of the daily high temperature above freezing for all the days being considered from the time of construction to the time of coring. Compared to the parameter of pavement in-service time, CDD has the advantage of considering both temperature and time when characterizing the field aging of asphalt pavements.

$$CDD = \begin{Bmatrix} \sum (T_{d\max} - 32), \text{ if } \mathrm{T_{dmax}} \geq 32 \\ 0, \text{ if } \mathrm{T_{dmax}} < 32 \end{Bmatrix} \tag{1}$$

Where:

T_{dmax} = daily max temperature, °F.

In the recently completed NCHRP project 09-49A, the long-term field performance of 53 warm mix asphalt (WMA) and 30 HMA pavement sections were monitored (*15*). Two round of pavement surveys were conducted in 2012/2013 and 2014/2015, respectively, to collect field distresses, including rutting, transverse cracking, and wheel-path longitudinal cracking. Figure 1 presents the wheel-path longitudinal crack length versus the corresponding pavement CDD at the time of pavement surveys.



(a) (b)

FIGURE 1 Wheel-path Longitudinal Crack Survey Results; (a) First Survey in 2012/2013, (b) Second Survey in 2014/2015 (Shen et al., 2017)

For the first survey results shown in Figure 1(a), pavements with less than 70,000 CDD showed no cracking, while those with over 70,000 CDD had measurable cracking (crack length over 20 feet). A similar trend was also observed for the second survey results, as shown in Figure 1(b). Examination of field cores sampled from pavements with wheel-path longitudinal cracks showed that these cracks initiated from the pavement surface and stopped within the asphalt layer, which was indicative of top-down fatigue cracking (*15*). Based on the survey results in Figure 1, TDC seemed to develop in asphalt pavements with over approximately 70,000 CDD of field aging. A similar finding was also reported by the 2009 NCAT Test Track research group experiment, where pavement cracks were found to start developing approximately four years after construction in Alabama weather (65,000 CDD) (*16*). Thus, 70,000 CDD was proposed as a preliminary critical field aging condition to evaluate TDC. Figure 2 presents a map showing the number of years required by different states to reach this preliminary CDD value. In general, warm climate states (e.g., Alabama, Florida, Texas, etc.) need approximately 4 years to achieve 70,000 CDD while a significantly longer time of up to 8 years is required for states in the cold climate (e.g., Michigan, Minnesota, Wisconsin, etc.).

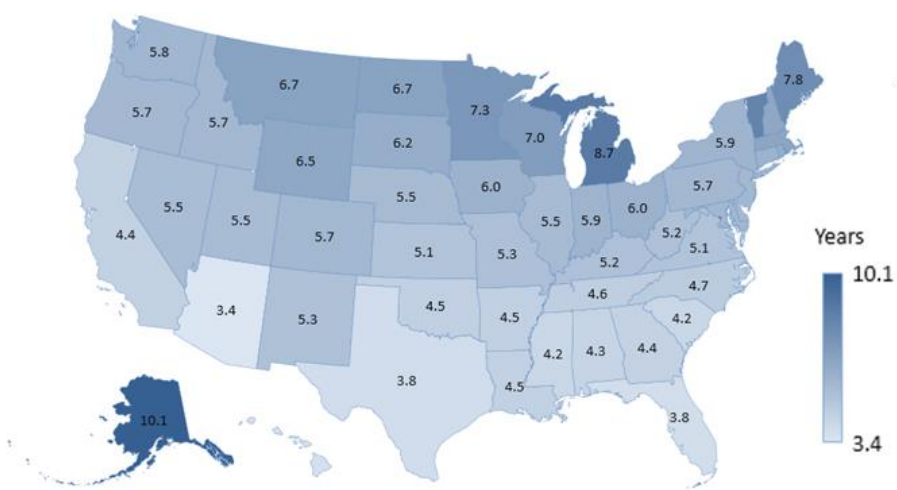


FIGURE 2 A Map showing the Number of Years to Reach 70,000 CDD

3. EXPERIMENTAL DESIGN TO SELECT REPRESENTATIVE AGING PROTOCOLS

Figure 3 presents the research methodology used to select a laboratory aging protocol to simulate 70,000 CDD of field aging. Materials used in the experiment were from five field projects in Washington, Michigan, and Alabama. For each field project, plant production mix and post-construction field cores were sampled and tested to characterize field aging. Four loose mix aging protocols of 5 days at 95°C, 6 hours at 135°C, 12 hours at 135°C, and 24 hours at 135°C were evaluated. In this study, only binder testsing was conducted due to limited number of field cores available. Asphalt binders extracted and recovered from plant mix and field cores were tested in the dynamic shear rheometer (DSR), bending beam rheometer (BBR), and Fourier transform infrared spectroscopy (FT-IR), to determine their rheological and oxidation properties. Test results were analyzed towards comparing the different aging protocols and determining their correlations with field aging.

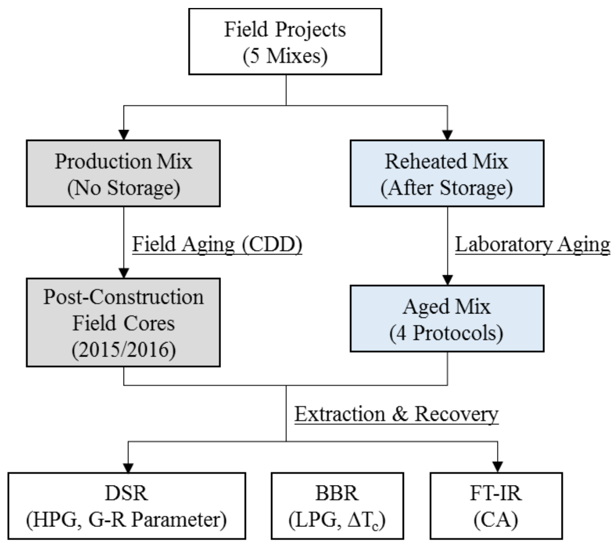


FIGURE 3 Research Methodology

3.1 Materials

Materials used in the experiment were from five field projects that covered a wide range of pavement age, climatic conditions, and mixture components. These projects were selected based on the availability of plant loose mix that were sampled during production. Two projects were from the NCHRP project 09-47A; one was on US-12 in Walla Walla, Washington, and the other was on County Road 513 near Rapid River, Michigan. The other three projects were from test sections on the NCAT Test Track, but they were constructed in different research cycles. Table 1 provides a brief summary of mixture components and construction and coring information for the five field projects.

TABLE 1 Summary of Field Projects

Mix ID	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Location	Rapid River, Michigan	Walla Walla, Washington	Auburn, Alabama	Auburn, Alabama	Auburn, Alabama
Mixture Type	HMA	HMA	HMA	HMA	HMA
Virgin Binder	PG 52-34	PG 64-28	PG 76-22 (SBS)	PG 67-22	PG 67-22
NMAS	12.5 mm	12.5 mm	9.5 mm	12.5 mm	12.5 mm
Gradation	Dense-Graded	Dense-Graded	Dense-Graded	Dense-Graded	Dense-Graded
RAP	17%	20%	0%	20%	0%
Construction Date	07/2010	04/2010	07/2009	09/2006	07/2000
Post-Construction Coring Date	09/2016	10/2016	10/2016	10/2016	01/2015
In-Service Time	6 years, 2 months	6 years, 6 months	7 years, 3 months	10 years, 1 month	14 years, 6 months
CDD	48,000	80,000	114,000	157,000	235,000

3.2 Sample Preparation

For each field project, sufficient amounts of plant mix were sampled during production and were stored in the NCAT laboratory. For specimen preparation, buckets with plant mix were first placed in an oven at 150°C for approximately three hours. Afterwards, the reheated mix was batched into individual samples of approximately 2,500 grams, which were then spread out in shallow pans and placed back in the over for further aging at the four conditions noted above. Mix samples aged for 5 days at 95°C were stirred once every 24 hours to ensure aging uniformity. As mentioned previously, post-construction field cores were included in the experiment to represent field aging. Considering the non-uniform aging of asphalt pavements with depth (*10, 17-18*), only the top one inch of the field cores were tested. In this study, asphalt binders were extracted (using trichloroethylene) and recovered from reheated plant mixes, laboratory aged mixes, and post-construction field cores in accordance with AASTHO T164 and ASTM D 5404, respectively. The extracted and recovered binders were then subjected to DSR, BBR, and FT-IR testing without additional aging using the rolling thin-film oven (RTFO) and pressure aging vessel (PAV). It should be noted that the impact of asphalt extraction and recovery on the rheological and chemical properties of asphalt binders was not considered in the study.

3.3 Laboratory Binder Tests

3.3.1 Dynamic Shear Rheometer

DSR was used to characterize the rheological properties of asphalt binders by measuring the complex shear modulus (G^*) and phase angle (δ) at a specific temperature and frequency. Extracted asphalt binders were first tested to determine the continuous high-temperature performance grade (HPG) per AASHTO R29 and M 320. In addition, the limited DSR frequency sweep test was conducted at three temperatures of 20, 30, and 40°C and with an angular frequency range of 0.1 to 10 rad/s. The maximum oscillation strain was controlled at one percent to ensure the asphalt binder was in the linear viscoelastic range. For data analysis, G^* and δ master curves were constructed by fitting the individual G^* and δ results at each temperature and frequency to the

Christensen-Anderson-Marasteanu (CAM) model (*19*), as expressed in Equation (2). The master curves were then utilized to calculate the Glover-Rowe (*G-R*) parameter using Equation (3) (*20-21*). The *G-R* parameter considers both binder stiffness and embrittlement and offers an indication of the cracking potential at intermediate temperature. Asphalt binders with higher *G-R* parameters are expected to have experienced a greater level of aging than those with lower *G-R* parameters.

$$G^* = G_g\left[1+\left(\frac{\omega_c}{\omega}\right)^v\right]^{-\frac{w}{v}}$$
$$\delta = \frac{90w}{\left[1+\left(\frac{\omega}{\omega_c}\right)^v\right]} \quad (2)$$

Where:

G_g = glass modulus, assumed equal to 1 GPa;
ω_c = crossover frequency;
ω = reduced frequency;
v and w = model coefficients.

$$G-R\,Parameter = \left\{\frac{G^*\left[\cos(\delta)^2\right]}{\sin(\delta)}\right\}_{T=15^\circ C,\, f=0.005 rad/s} \quad (3)$$

3.3.2 Bending Beam Rheometer

BBR was used to characterize the resistance of asphalt binders to thermal cracking at low temperatures. The test was conducted to determine the low-temperature performance grade (LPG) based on the creep stiffness (*S*) and m-value results per AASHTO T313. The ΔT_c parameter, which is defined as the numerical difference between the continuous LPG determined from the *S* criteria and the grade determined from the m-value criteria (*22*), was also determined. The ΔT_c parameter is indicative of the cracking potential of asphalt binders; specifically, binders with a more negative ΔT_c are more likely susceptible to block cracking than those with a less negative ΔT_c.

3.3.3 Fourier Transform Infrared Spectroscopy

FT-IR was used to measure the infrared spectrum of asphalt binders and determine their compositional changes with aging. The test was conducted using a Nicolet 6700 FT-IR spectrometer with attenuated total reflectance (ATR) setup. The carbonyl area (*CA*), defined as the integrated peak area for the wavelength range from 1820 to 1650 cm^{-1} (*23*), was used to evaluate the oxidation level of asphalt binders extracted from mixes with various aging protocols. Asphalt binders with higher *CA* are expected to have experienced a greater level of oxidative aging than those with lower *CA*.

4. TESTS RESULTS AND DATA ANALYSIS

This section presents the DSR, BBR, and FT-IR results of asphalt binders extracted from laboratory aged mixes and post-construction field cores. Test results were analyzed to evaluate the effects of laboratory loose mix aging on binder rheological and oxidation properties. Additionally, the correlation of field aging with these aging protocols was explored. Finally, protocols that were representative of 70,000 CDD of field aging were selected for the NCAT TDC experiment.

4.1 Comparisons of Laboratory Aging Protocols

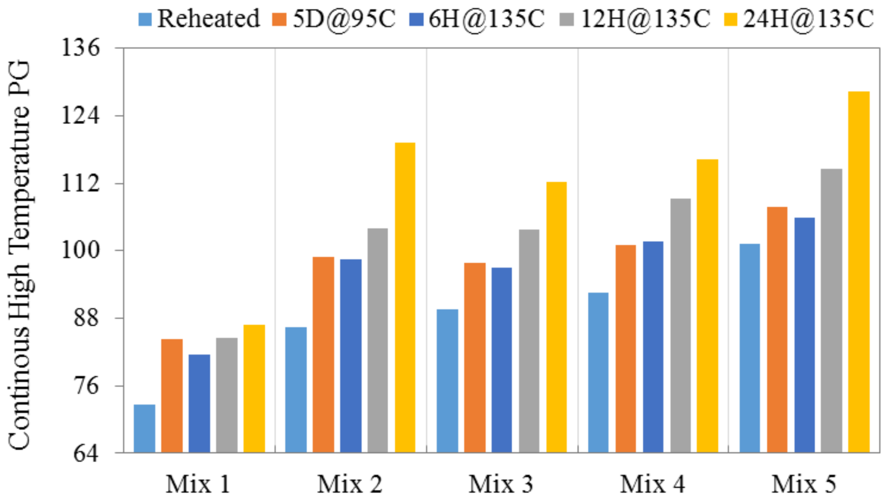
4.1.1 Continuous PG Results

Figure 4 presents the continuous HPG and LPG results of asphalt binders extracted from reheated and laboratory aged mixes. As shown in Figure 4(a), for all five mixes, asphalt binders from laboratory aged mixes showed consistently higher HPG than those from the corresponding reheated mixes, which indicated that the aging protocols evaluated in this study yielded significant level of asphalt aging. The average increase in the continuous HPG for different aging protocols varied from 8.4 to 24.1. As expected, longer aging times at 135°C showed greater increases in the continuous HPG. For all mixes except Mix 4, the 5-day, 95°C protocol yielded a slightly higher increase in the HPG than the 6-hour, 135°C protocol. The average difference in the continuous HPG between these two aging protocols was approximately 1.1, which was not considered practically significant. Similar trends were also observed for the continuous LPG results in Figure 4(b). In general, the 24-hour, 135°C protocol yielded the greatest increase in both HPG and LPG, followed by the 12-hour, 135°C protocol, 5-day, 95°C protocol, and 6-hour, 135°C protocol, respectively.

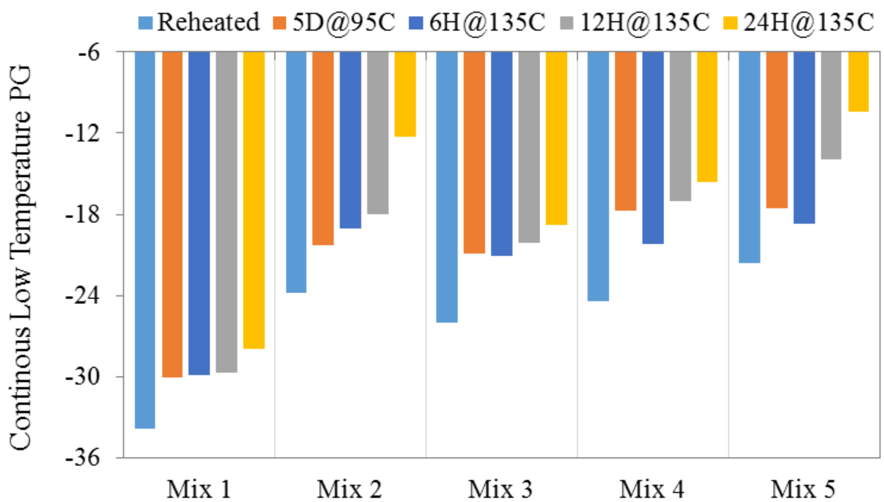
4.1.2 Cracking Parameter Results

Figure 5 presents the *G-R* parameter results in Black space, where the G^* at 15°C and 0.005 rad/s of extracted asphalt binders were plotted against the corresponding δ values. A consistent trend was observed for all mixes that asphalt binders extracted from laboratory aged mixes were located closer to the upper left corner on the Black space diagram than those from the reheated mixes were, which indicated that asphalt binders after aging had increased stiffness and loss of relaxation properties. Based on the “travelled” distances on the Black space diagram, the 24-hour, 135°C protocol produced the most significant level of asphalt aging, followed by the 12-hour, 135°C protocol, 5-day, 95°C protocol, and 6-hour, 135°C protocol, respectively. These results were in agreement with the continuous PG results in Figure 4.

Figure 6 presents the BBR ΔT_c results of asphalt binders extracted from reheated and laboratory aged mixes. As mentioned previously, asphalt binders with a more negative ΔT_c are more susceptible to cracking due to reduced relaxation properties. As can be seen, the ΔT_c of asphalt binders from laboratory aged mixes was consistently lower (i.e., more negative) than those of the corresponding reheated mixes. The 12-hour and 24-hour, 135°C protocols exhibited the two lowest ΔT_c values for all mixes. No consistent trend was found for the ΔT_c comparisons between the 5-day, 95°C and 6-hour, 135°C protocols; but in most cases, the difference in the ΔT_c between these two aging protocols was less than 1.0.



(a)



(b)

FIGURE 4 Continuous PG Results of Extracted Asphalt Binders with Various Loose Mix Aging Protocols; (a) High-Temperature, (b) Low-Temperature

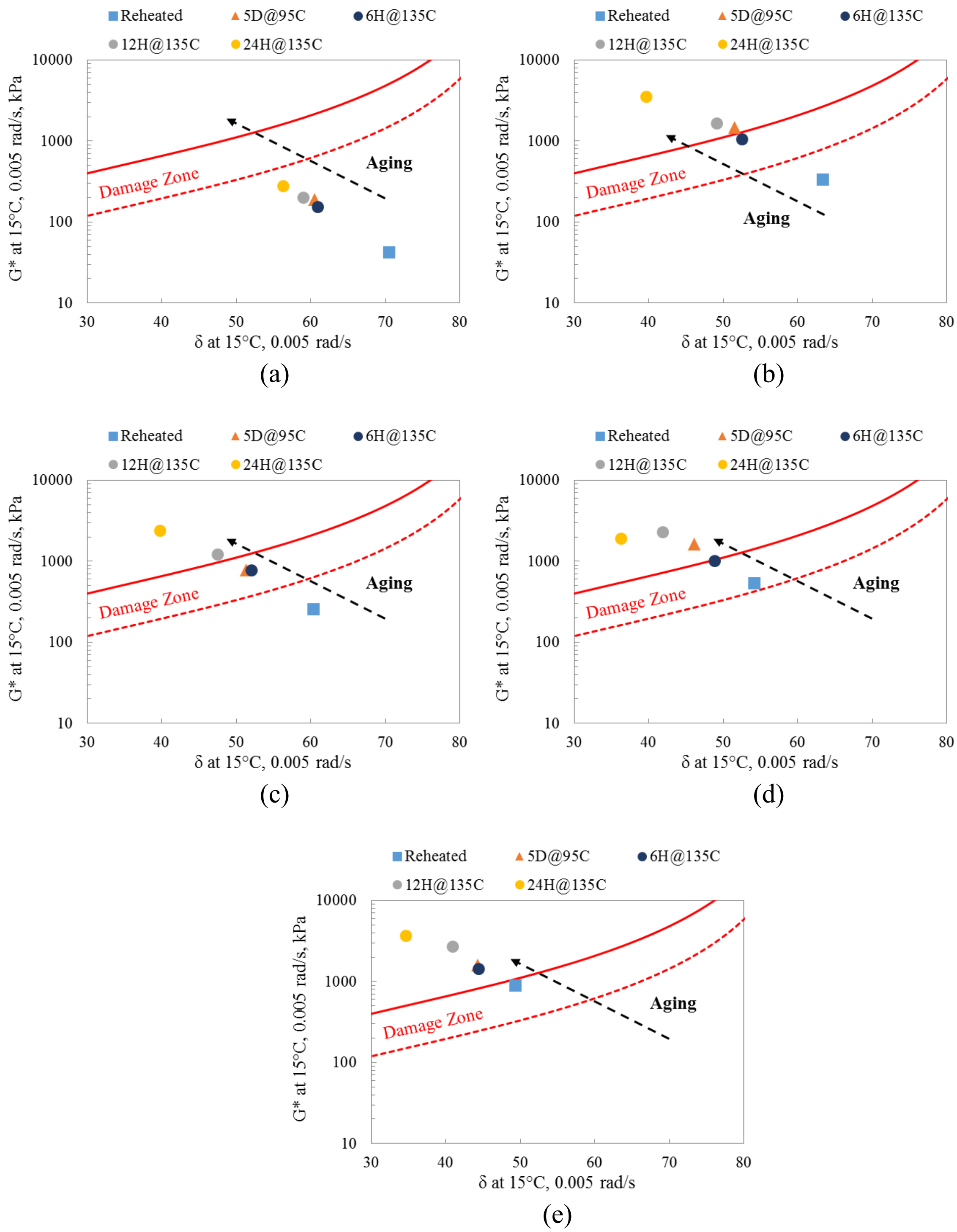


FIGURE 5 *G-R* Parameter Results in Black Space Diagram; (a) Mix 1, (b) Mix 2, (c) Mix 3, (d) Mix 4, (e) Mix 5

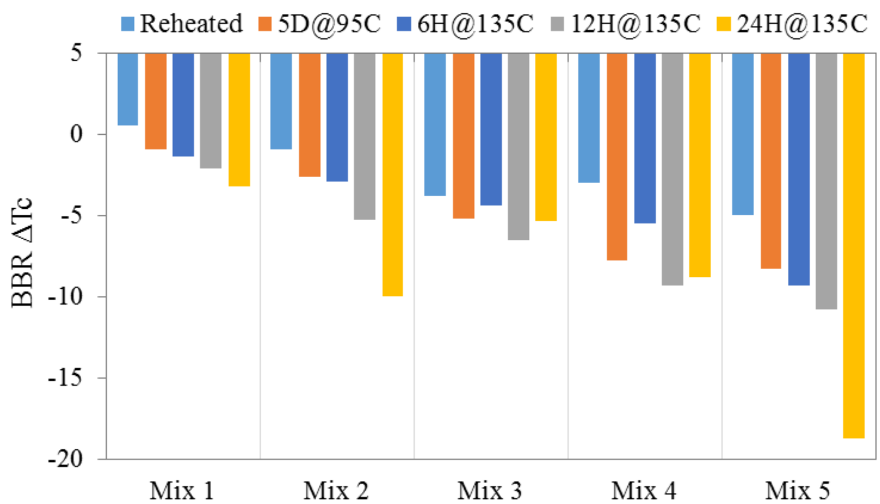


FIGURE 6 BBR ΔT_c Results of Extracted Asphalt Binders with Various Loose Mix Aging Protocols

4.1.3 FT-IR CA Results

Figure 7 presents the FT-IR *CA* results of asphalt binders extracted from reheated and laboratory aged mixes. In general, the results fell in line with the continuous PG and *G-R* parameter results shown in Figure 4 and Figure 5, respectively. Asphalt binders extracted from 135°C mixes showed a consistent increase in *CA* with extensions in aging time, which indicated that more polar oxygen-containing functional groups were formed during the process. For all mixes except Mix 4, extracted binders from the 5-day, 95°C mix had a *CA* that was between those of binders from the 6-hour and 12-hour, 135°C mixes. Based on the FT-IR *CA* results, the four loose mix aging protocols were ranked in the following order in terms of the resultant aging level: 6-hour, 135°C < 5-day, 95°C < 12-hour, 135°C < 24-hour, 135°C.

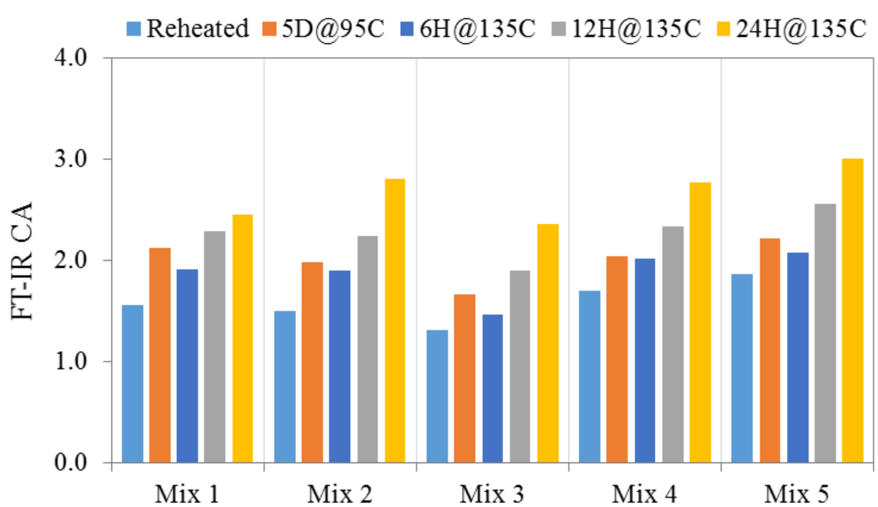


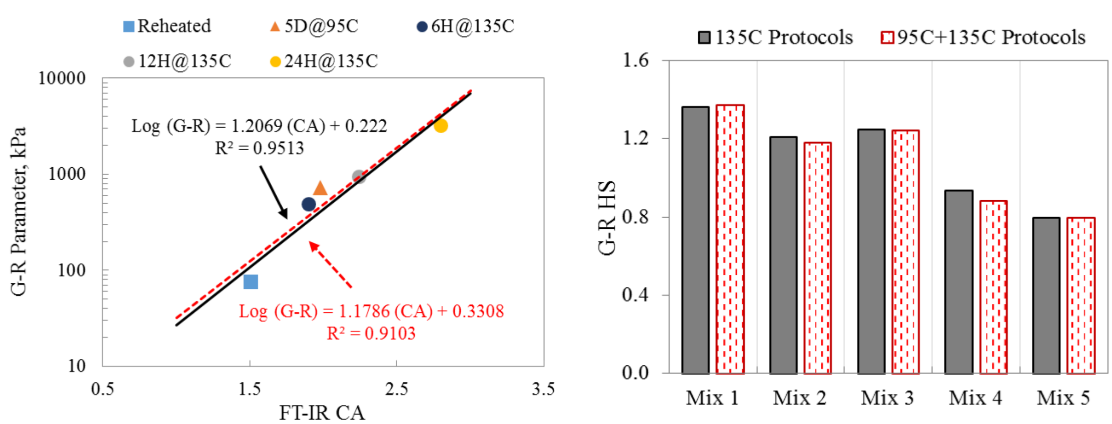
FIGURE 7 FT-IR *CA* Results of Extracted Asphalt Binders with Various Loose Mix Aging Protocols

4.1.4 Hardening Susceptibility Results

Previous literature reported that aging at 135°C could change the relationship between chemical oxidation and physical hardening of asphalt binders due to the physicochemical disruption of its microstructure at such an elevated temperature (*24*). This oxidation-hardening relationship was typically referred to as hardening susceptibility (*20, 25*). In this study, the Glover-Rowe hardening susceptibility (*G-R HS*) parameter was used to explore the impact of loose mix aging on the oxidation-hardening relationship of asphalt binders. As expressed in Equation 4, the *G-R HS* was defined as the ratio of change in the logarithm of the *G-R* parameter over the change in the FT-IR *CA* with aging (*26*).

$$G-R\,HS = \frac{d\left[\log(G-R)\right]}{d(CA)} \tag{4}$$

Figure 8(a) presents an example to illustrate the determination of *G-R HS*. In the figure, the *G-R* parameter and *CA* results were fitted using a semi-log linear relationship and the slope of the trendline represented the *G-R HS*. The dashed line represented the trendline determined based on all aging protocols evaluated in this study, while the solid trendline was only for protocols at 135°C. The coefficient of determination (i.e., R^2) of both trendlines were higher than 0.9, indicating goodness of the fit. In addition, the two trendlines almost overlapped each other. Similar trends were also shown by the other four mixes, but the results are not presented due to space limitation. Figure 8(b) summarizes the comparison of *G-R HS* results for all aging protocols versus those only at 135°C. As shown, for the five mixes evaluated in this study, the two groups of aging protocols exhibited similar *G-R HS* results, indicating no significant difference in the oxidation-hardening relationship of asphalt binders aged at 95°C versus 135°C.



(a) (b)

FIGURE 8 *G-R HS* Results; (a) Example of Mix 2 Data, (b) Comparison of Loose Mix Aging Protocols at 95°C and 135°C

4.2 Correlation of Field Aging with Laboratory Aging Protocols

Figure 9 presents the continuous HPG results to determine the correlation of field aging with laboratory loose mix aging protocols. The pattern-filled bars represent the difference in the continuous HPG of asphalt binders extracted from post-construction field cores versus the corresponding plant mixes that were tested immediately after sampling, and the solid-filled bars represent the difference between the laboratory aged mixes and reheated mixes. Mix 3 was excluded from the analysis due to the use of styrene-butadiene-styrene (SBS) polymer modified binder, which has been extensively reported with significantly different aging characteristics as neat binders (*27-29*).

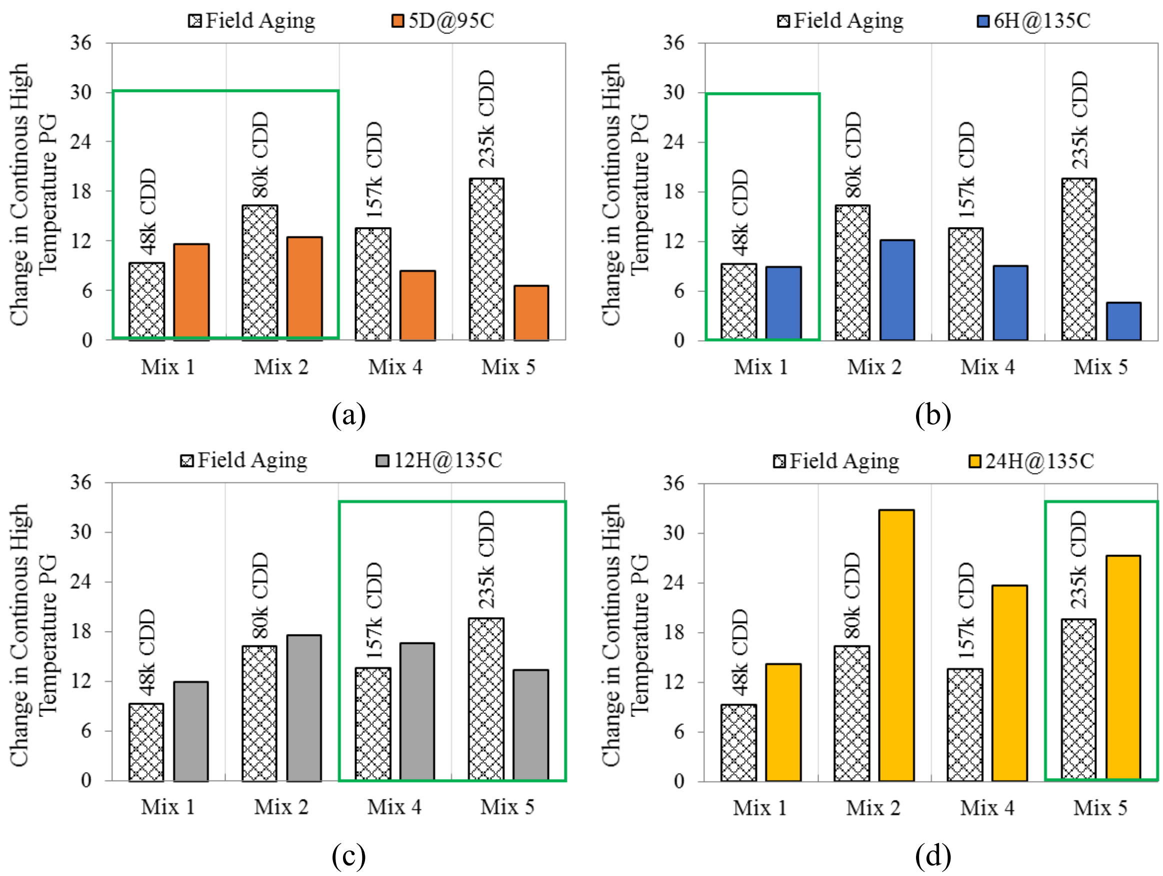


FIGURE 9 Comparison of Field Aging and Laboratory Loose Mix Aging Protocols; (a) 5-day, 95°C, (b) 6-hour, 135°C, (c) 12-hour, 135°C, (d) 24-hour, 135°C

As shown in Figure 9(a), the 5-day, 95°C protocol was more severe than field aging of approximately 48,000 CDD (Mix 1), as indicated by a greater increase in the continuous HPG. The opposite trend, however, was shown for the other mixes with field aging of approximately 80,000, 157,000, and 235,000 CDD, respectively. These results indicated that the 5-day, 95°C protocol yielded asphalt aging that was representative of field aging between 48,000 and 80,000 CDD. The same approach was applied for the other three loose mix aging protocols [Figure 9(b) to Figure 9(d)], and their representative CDD ranges are summarized as follows:

- 5-day, 95°C protocol: 48,000 to 80,000 CDD
- 6-hour, 135°C protocol: approximately 48,000 CDD
- 12-hour, 135°C protocol: 80,000 to 157,000 CDD
- 24-hour, 135°C protocol: greater than 235,000 CDD

As discussed previously, 70,000 CDD was identified as a preliminary critical field aging condition for evaluating TDC. Therefore, based on the data shown in Figure 9, loose mix aging of 5 days at 95°C was the most representative aging protocol.

4.3 Selection of Alternative Aging Protocol at 135°C

Although loose mix aging of 5 days at 95°C was identified as the most appropriate protocol to simulate 70,000 CDD of field aging, this protocol might not be suitable for practical implementation due to long time span. Therefore, test results were further analyzed to determine an alternative aging protocol at 135°C that yielded an equivalent level of aging as the 5-day, 95°C protocol. Figure 10(a) presents an example of the FT-IR *CA* results of Mix 2. To determine the alternative aging protocol, the fast-rate constant-rate oxidation kinetic model (*30*), described in Equation 5, was first used to fit the *CA* results of laboratory aged mixes at 135°C. Once the model coefficients were determined, the equivalent aging time at 135°C was then calculated based on the measured *CA* of the 5-day, 95°C protocol [Figure 10(a)]. For the continuous HPG and *G-R* results, linear and semi-log linear models were used to determine the equivalent aging times, respectively. As shown in Figure 10(b), for both oxidation and rheological parameters, similar level of asphalt aging was achieved by loose mix aging protocols of 5 days at 95°C and approximately 8 hours at 135°C. Thus, the 8-hour, 135°C protocol was recommended as an alternative aging protocol to simulate 70,000 CDD of field aging.

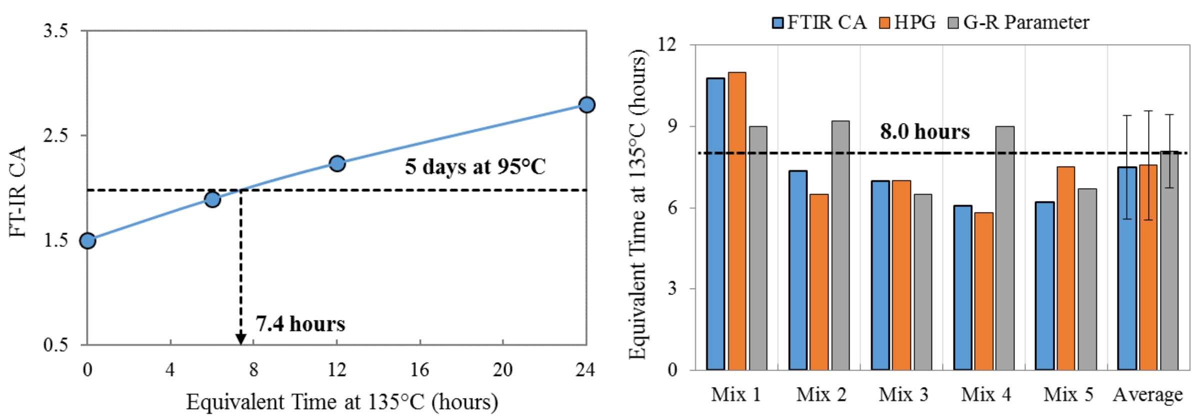
$$CA = CA_0 + k_c t + M(1 - e^{-k_f t}) \tag{5}$$

Where:

CA_0 = CA of asphalt binder extracted from the reheated mix;

t = aging time at 135°C;

k_c, k_f, and M = model coefficients.



(a) (b)

FIGURE 10 Determination of Equivalent Aging Time at 135°C; (a) Example of Mix 2 FI-IR *CA* Results, (b) Summary of All Results

5. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to select a laboratory mix aging protocol for the NCAT TDC experiment. Four different loose mix aging protocols were evaluated in terms of their effects on rheological and oxidation properties of asphalt binders. In addition, their correlations with field aging were investigated based on the concept of CDD. Based on the results of this study, the following conclusions were obtained:

- TDC was found to develop in asphalt pavements with over approximately 70,000 CDD; thus, this CDD value was identified as the critical field aging condition for evaluating TDC.
- Based on the rheological and oxidation results, the 24-hour, 135°C protocol yielded the most significant level of asphalt aging, followed by the 12-hour, 135°C protocol, 5-day, 95°C, protocol, and 6-hour, 135°C protocol, respectively.
- The *G-R HS* parameter was used to explore the effect of loose mix aging on the oxidation-hardening relationship of asphalt binders. For the five mixes evaluated in this study, no significant difference in the *G-R HS* results was shown for mixes aged at 95°C versus 135°C.
- Among the four loose mix aging protocols evaluated in this study, the 5-day, 95°C protocol was most representative of 70,000 CDD of field aging.
- Based on the HPG, *G-R* parameter, and *CA* results, the loose mix aging protocol of 8 hours at 135°C was anticipated to yield an equivalent level of aging as that of 5 days at 95°C. Therefore, the 8-hour, 135°C protocol was recommended as an alternative, but more practical, protocol to simulate 70,000 CDD of field aging.

In this study, the representative loose mix aging protocols were determined based on a limited number of asphalt mixtures and were primarily based on the HPG results. Thus, future research is needed to verify the selected protocols using additional mixtures and binder properties. Additionally, there is a need for future research to evaluate the aging characteristics of polymer modified asphalt binders. Furthermore, mixture performance testing are recommended to validate the equivalency between the 5-day, 95°C and 8-hour, 135°C loose mix aging protocols. Finally, it is recommended to continue monitoring the performance of pavements with TDC to validate the preliminary critical field aging of 70,000 CDD.

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REFERENCES

1. Myers, L. A., Roque, R., & Ruth, B. E. (1998). Mechanisms of surface-initiated longitudinal wheel path cracks in high-type bituminous pavements. *Journal of the Association of Asphalt Paving Technologists*, 67.
2. Uhlmeyer, J., Willoughby, K., Pierce, L., & Mahoney, J. (2000). Top-down cracking in Washington state asphalt concrete wearing courses. *Transportation Research Record: Journal of the Transportation Research Board,* (1730), 110-116.
3. Svasdisant, T., Schorsch, M., Baladi, G., & Pinyosunun, S. (2002). Mechanistic analysis of top-down cracks in asphalt pavements. *Transportation Research Record: Journal of the Transportation Research Board*, (1809), 126-136.
4. Han, G., Clopotel, C. S., & Bahia, H. U. (2013). Effects of high modulus asphalt binders on performance of typical asphalt pavement structures. *Construction and Building Materials*, 44, 207-213.
5. Moore, N. (2016). Evaluation of Laboratory Cracking Tests Related to Top-Down Cracking in Asphalt Pavements. Auburn University.
6. Bell, C. A., AbWahab, Y., Cristi, M. E., & Sosnovske, D. (1994). *Selection of laboratory aging procedures for asphalt-aggregate mixtures* (No. SHRP-A-383). Strategic Highway Research Program.
7. Newcomb, D., Martin, A.E., Yin, F., Arambula, E., Park, E.S., Chowdhury, A., Brown, R., Rodezno, C., Tran, N., Coleri, E. and Jones, D. (2015*). Short-term laboratory conditioning of asphalt mixtures* (No. Project 09-52).
8. Islam, M. R., Hossain, M. I., & Tarefder, R. A. (2015). A study of asphalt aging using Indirect Tensile Strength test. *Construction and Building Materials*, 95, 218-223.
9. Howard, I. L., & Doyle, J. D. (2015). Durability Indexes via Cantabro Testing for Unaged, Laboratory-Conditioned, and One-Year Outdoor-Aged Asphalt Concrete. In *Transportation Research Board 94th Annual Meeting* (No. 15-1366).
10. Elwardany, M. D., Yousefi Rad, F., Castorena, C., & Kim, Y. R. (2017). Evaluation of asphalt mixture laboratory long-term ageing methods for performance testing and prediction. *Road Materials and Pavement Design*, 18(sup1), 28-61.
11. Braham, A. F., Buttlar, W. G., Clyne, T. R., Marasteanu, M. O., & Turos, M. I. (2009). The effect of long-term laboratory aging on asphalt concrete fracture energy. *Journal of the Association of Asphalt Paving Technologists,* 78.
12. Reinke, G., Hanz, A., Herlitzka, D., Engber, S., & Ryan, M. (2015, April). Further investigations into the impact of REOB & paraffinic oils on the performance of bituminous mixtures. In *FHWA Expert Task Group Meeting*, Fall River, Mass7.
13. Kim, Y. R., Castorena, C., Rad, F. Y., Elwardany, M., Underwood, S., Farrar, M. J., & Glaser, R. R. (2015). *Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction. Quarterly Report* (April-June, 2015), National Cooperative Highway Research Program, No. Project, 9-54.
14. Dauzats, M., & Rampal, A. (1987). Mechanism of surface cracking in wearing courses. In *International Conference on the Structural Design*.
15. Shen, S. H., Wen, H. F., Mohammad, L., Lund, N., Faheem, A., Zhang, W. G., & Wu, S. H. (2013). *Performance of WMA technologies*: stage II-long-term field performance. Transportation Research Board of the National Academies, Washington, DC.
16. Tran, N. (2010). Evaluation of Warm Mix Asphalt with High RAP on NCAT Pavement Test Track. NCAT
17. Turner, F. (2008). WRI Research Related to the Optimal Timing of Preventive Maintenance

for Addressing Environmental Aging. Western Research Institute.

18. Yin, F., A. Epps Martin, E. Arambula-Mercado, and D. Newcomb. 2017. Characterization of Non-Uniform Field Aging in Asphalt Pavements. *Construction and Building Materials*, Article reference JCBM10898.
19. Santagata, E., Anderson, D. A., & Marasteanu, M. (1996). A rheological investigation on the physical hardening of modified asphalt binders. In *Eurasphalt & Eurobitume Congress*, Strasbourg, 7-10 May 1996. Volume 3. Paper E&E. 5.151.
20. Glover, C. J., Davison, R. R., Domke, C. H., Ruan, Y., Juristyarini, P., Knorr, D. B., & Jung, S. H. (2005). Development of a new method for assessing asphalt binder durability with field validation. Texas Dept Transport, 1872.
21. Rowe, G. M. (2011). Prepared Discussion for the AAPT paper by Anderson et al.: Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking. Journal of the Association of Asphalt Paving Technologists, 80, 649-662.
22. Anderson, R. M., King, G. N., Hanson, D. I., & Blankenship, P. B. (2011). Evaluation of the relationship between asphalt binder properties and non-load related cracking. *Journal of the Association of Asphalt Paving Technologists*, 80.
23. Liu, M., Ferry, M. A., Davison, R. R., Glover, C. J., & Bullin, J. A. (1998). Oxygen uptake as correlated to carbonyl growth in aged asphalts and asphalt Corbett fractions. *Industrial & engineering chemistry research*, 37(12), 4669-46742.
24. Petersen, J. C. (2009). A review of the fundamentals of asphalt oxidation: chemical, physicochemical, physical property, and durability relationships. *Transportation Research E-Circular*, (E-C140).
25. Domke, C., Davison, R., & Glover, C. (1999). Effect of oxidation pressure on asphalt hardening susceptibility. *Transportation Research Record: Journal of the Transportation Research Board*, (1661), 114-121.
26. Yin, F et al. (2017). Characterizing the Long-Term Rejuvenating Effectiveness of Recycling Agents on Asphalt Blends and Mixtures with High RAP and RAS Contents. Accepted by 2017 AAPT or 2018 RMPD. www.tfhrc.gov/pavement/pccp/pavespec. Accessed March 5, 2017.
27. Sun, L., Wang, Y., & Zhang, Y. (2014). Aging mechanism and effective recycling ratio of SBS modified asphalt. *Construction and Building Materials*, 70, 26-35.
28. Ruan, Y., Davison, R. R., & Glover, C. J. (2003). The effect of long-term oxidation on the rheological properties of polymer modified asphalts. *Fuel*, 82(14), 1763-1773.
29. Ouyang, C., Wang, S., Zhang, Y., & Zhang, Y. (2006). Improving the aging resistance of styrene–butadiene–styrene tri-block copolymer modified asphalt by addition of antioxidants. *Polymer degradation and stability*, 91(4), 795-804.
30. Jin, X., Han, R., Cui, Y., & Glover, C. J. (2011). Fast-rate–constant-rate oxidation kinetics model for asphalt binders. *Industrial & Engineering Chemistry Research*, 50(23), 13373-13379.